[redacted]

February 6, 1969

Rec'd 2/6/69

Contracting Officer
Post Office Box 6788
Fort Davis Station
Washington, D.C. 20020

Dear Sir:

Attached herewith are three copies of the final report covering Phases 1 and 2 of Contract [redacted] Task Order 18, Work Order 1. This report presents an evaluation and error analysis of the two [redacted] Model 552A101 High Precision Stereo Viewers. Recommendations are included for future actions which can attain the desired measurement accuracies.

If you have any questions on this report, please contact [redacted]r myself at our [redacted] [redacted]acility.

Sincerely,

[redacted]
Director
Washington Systems Laboratory

JTK:am

Attachments 3

[redacted]

Rec'd 2/6/69

STAT

REPORT ON EVALUATION OF TWO MENSURATION
TABLES AND PRELIMINARY ERROR ANALYSIS

STAT

BEST COPY
Available

pointing accuracy is at least as good as indicated above. Since two readings were taken at all subsequent measurements, the standard error of the average can be found by dividing the standard deviation of one setting by the square root of two or:

$$s_x = \pm 0.0008 \text{ mm.}$$

$$s_y = \pm 0.0008 \text{ mm.}$$

Hence, the errors in pointing are of the same order of magnitude as the errors in the grid.

C. Mechanical Operating Problems

The following erraticisms in mechanical operating characteristics were noted during the evaluation procedure.

(1.) Drift. The most noticeable and identifiable cause of non-reproducability of coordinate readings was drift -- i.e., it was noted that the pointing mark could be set at a grid intersection, and then would drift away from the intersection with time. The coordinate counters did not move during this drift -- i.e., different readings were obtained when the measuring point was moved back to the grid intersection. The following set of readings indicate the variations in coordinate readings for a given point with time. (Note: the x coordinate remained constant; drift occurring in the y direction only.)

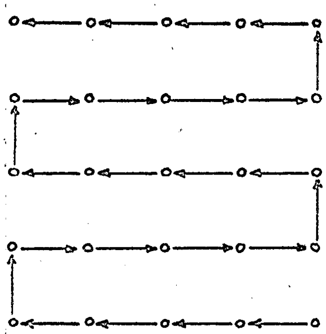
Time	y Coordinate Reading (mm.)	
12:16	72.186	
:17	.189	
:18	.190	net change:
:20	.192	12 microns
:22	.194	
:56	.198	

These data were collected at the right stage of Instrument No. 104. However, comparable drifts were noted at the left stage of No. 104 and the right stage of No. 101. In a 15-minute trial, no drift was noted at the left stage of No. 101. There was no drift in the x direction at any of the four stages.

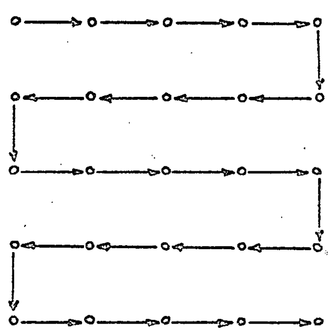
Further evidence of the "drift" in y-coordinate readings, and the nature of the drift, can be seen by comparing the readings obtained on two passes over the 25 points measured on the left half of the right stage on Instrument No. 104. (There were 5 lines of 5 points each; pass 1 was made in the order shown in Figure 1b. The values in Figure 1c are the difference in y readings for the two passes.)

Note that the discrepancy in y-coordinate measurements increased as the time between readings at the points increased -- i.e., the two readings for the point in the upper left corner were taken in succession with little time lapse or movement of the optical head between readings, whereas the series of readings was started with the point in the lower right corner and the pass 2 readings for this point were not taken until the end of the series. Note further that the discrepancies for a given row are fairly consistent and major changes seem to occur between rows. This leads one to suspect the instrument is "binding" in the y motion; the major "binds" occurring when the reading head is moved from one row to the next. A major disruption in the pattern occurs in the fourth row from the top. However, it is possible some of the binding "relaxed" in moving from the fifth point to the fourth point in that row.

It should also be noted that if the instrument was left in the position at which the final reading in pass 2 was obtained, the aforementioned drift tended to bring the instrument back to the original reading -- i.e., the 8 micron discrepancy in the point at the lower right corner in Figure 1 tended to decrease with time. Further, it was noted that if the reading head was



(a) Pass 1



(b) Pass 2

1	3	3	4	2
5	4	4	6	7
6	6	7	6	6
3	3	3	3	7
5	5	7	8	8

(c) y-coordinate discrepancies (microns) (Pass 1 − Pass 2)

Figure 1. Example of Drift in y-Coordinates
(50 mm. grid; Serial No. [redacted] right stage, left half)

STAT

moved rapidly back and forth in the y direction, it was possible to obtain the original reading.

From the above observations, it is hypothesized that the mechanical operation of the instrument is not satisfactory -- i.e., there appears to be a tendency for the reading head to "stick" or "bind" in the y direction. This binding may release gradually, as evidenced by the slow drift of the reading head in the y direction, or in spurts as indicated by the readings in row four in Figure 1.

(2.) "Stuttering." When y motion of the reading head was initiated by the joy stick, a noticeable "stuttering" occurred, clearly visible to the operator as an apparent vibration in the image. Further, when the instrument reading head was in motion in the y direction, a "groaning" noise was clearly audible to the operator or anyone in the immediate vicinity. These observations lend credence to the belief that the y motion of the instrument is not functioning properly.

The vibrations and noises were noted at both stages of both instruments.

(3.) Variations in focus. Another indication of improper motion in the reading head is the fact that the focus changed as the reading head travelled over the area of the calibration plate -- i.e., the focus could be set for one grid intersection and then, when the reading head was moved to another intersection and another part of the calibration plate, the grid would be slightly out of focus; at still another point, it might be back in focus. This phenomenon indicates the reading head is not moving in a plane parallel to the grid plate. Apparently, the reading head moves in the vertical direction while traversing the grid plate. Again, this could be due to binding in the mechanical operation of the instrument.

II. EVALUATION OF SERIAL [redacted] RIGHT STAGE

A. Measuring Procedure

It was not possible to purchase a 9 x 18-inch grid of sufficient quality for the evaluation. A 9 x 9-inch grid plate was purchased, having a rectangular grid mesh of 10 millimeters, and a calibrated accuracy of $\pm$0.8 microns in both the x and y directions. Not all of the available grid intersections were used in the evaluation procedure -- the spacing between rows and between columns being 50 millimeters for the evaluation. Since the grid plate was roughly half the size of the stage of the instrument, it was necessary to measure the grid plate in two positions. The readings taken with the grid on the right side of the stage were then tied to the readings taken on the left side through the use of a standard rotation-translation transformation based on the grid points along the common edge which overlapped at the center of the stage. In all, then, the total area in which grid measurements were taken was 200 mm. by 400 mm., with a point spacing of 50 mm. (approximately 2 inches); resulting in a 5 x 9 grid (8 x 16-inch), for a total of 45 points.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The instrument readings were transformed to the "perfect" grid through the use of a least-squares rotation-translation transformation which maintained the geometric integrity of the instrument readings. This permits one to assess the mensuration accuracy of the instrument in its present state -- i.e., without any corrections or adjustments to the basic readings. (The instrument readings have merely been rotated and translated to give the best fit to the grid; their relative positions have not been changed.) Figure 2 indicates the errors obtained at the instrument in its present state. The black lines represent the perfect grid, and the blue lines represent the grid as it was measured by the instrument. Note that the errors have been plotted at a greatly exaggerated scale as compared to the scale of the grid. Analysis of the data for Figure 2 indicates the mean magnitudes of the errors in the x and y coordinates for the 45 points to be:

$$m_x = 0.0100 \text{ mm.} = 10.0 \text{ microns}$$

$$m_y = 0.0148 \text{ mm.} = 14.8 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = +0.0075\% \text{ (7.5 microns per 100 mm.)}$$

$$dM_y = +0.0240\% \text{ (24.0 microns per 100 mm.)}$$

and the non-orthogonality of the axes to be:

$$d\beta = 0.000094 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of Axes

It is possible to remove the effects of x and y scale errors and non-orthogonality of the axes by transformation of the instrument readings through the use of the following transformation equations:

$$x_a = x_m \cdot (1-dM_x) - y_m(d\beta)$$

$$y_a = y_m \cdot (1-dM_y)$$

where (x_a, y_a) are the coordinates after adjustment and (x_m, y_m) are the measured coordinates. Substituting the values for scale errors and non-orthogonality given in (2) above, the equations become:

$$x_a = (+0.999925)x_m - (0.000094)y_m$$

$$y_a = (+0.999760)y_m$$

(The values for the scale errors and non-orthogonality were determined through the use of a least squares adjustment of the instrument readings from the 45 points.)

The red lines in Figure 2 indicate the values obtained for the grid after adjustment for the scale errors and non-orthogonality of axes. Note the "fit" is considerably improved. The mean magnitudes of the errors in the x and y coordinates after adjustment are as follows:

$$m_{x_a} = 0.0040 \text{ mm.} = 4.0 \text{ microns}$$

$$m_{y_a} = 0.0031 \text{ mm.} = 3.1 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the blue lines) for each grid position are given in Table 1, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-othogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 60% in the x coordinates and 79% in the y coordinates can be obtained by the utilization of the adjustment equations.

To summarize, errors as represented by the blue lines can be expected if the "raw" readings as obtained from the instrument in its present state are utilized; the errors can be reduced to those indicated by the red lines through transformation of the instrument readings utilizing the equations given above. However, it must be remembered the effects of drift and stuttering have probably been averaged out through the use of the average of replicated readings at the points and the adjustment procedure. Larger errors could be encountered if single readings are taken at points distributed

IV. EVALUATION OF SERIAL NO. [redacted] RIGHT STAGE

A. Measuring Procedure

The measuring procedure was the same as that described for the left stage of Serial No. [redacted] - i.e., the grid plate was measured in two positions and then tied together, resulting in a 100 mm. grid spacing and a total of 15 points.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The procedure was the same as described previously. The results are presented graphically in Figure 4. The mean magnitudes of the errors in the x and y coordinates for the 15 points were found to be:

$$m_x = 0.1289 \text{ mm.} = 128.9 \text{ microns}$$

$$m_y = 0.0791 \text{ mm.} = 79.1 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = -0.0025\% \quad (2.5 \text{ microns per } 100 \text{ mm.})$$

$$dM_y = +0.0124\% \quad (12.4 \text{ microns per } 100 \text{ mm.})$$

and the non-orthogonality of the axes to be:

$$d\beta = +0.002555 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of axes.

Substituting the specific values for scale errors and non-orthogonality given above in the previously cited adjustment equations results in the following:

$$x_a = (+1.000025)x_m - (0.002555)y_m$$

$$y_a = (+0.999875)y_m$$

The mean magnitudes of the errors in the x and y coordinates after adjustments are as follows:

$$m_{x_a} = 0.0045 \text{ mm.} = 4.5 \text{ microns}$$

$$m_{y_a} = 0.0050 \text{ mm.} = 5.0 \text{ microns}$$

Note that the original error values for this stage are very high compared to the other three stages. This is due to a very poor relative alignment of the axes -- i.e., the non-orthogonality is exceptionally high (0.00256 radians, or approximately $0^\circ 09'$). Note further, however, that the errors after adjustment compare favorably in magnitude with those of the other three stages. Thus, the non-orthogonality can be compensated for adequately through the adjustment equations.

The errors in the raw coordinate readings (indicated by the blue lines) for each grid position are given in Table 3, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 97% in the x coordinates and 94% in the y coordinates can be obtained by the utilization of the adjustment equations.

Table 3 - Errors in Grid Coordinates

Instrument Serial [redacted] Right Stage STAT

Grid Position (mm.)	Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
y_g	e_x	e_y	e_{x_a}	e_{y_a}
+100	+187	-115	- 8	+ 1
+100	+197	- 49	+ 4	+ 2
+100	+187	+ 21	- 4	+ 8
+100	+189	+ 83	- 1	+ 7
+100	+191	+135	+ 4	- 5
0	+ 3	-137	- 1	- 9
0	+ 12	- 70	+10	- 6
0	- 2	+ 4	- 2	+ 4
0	- 2	+ 59	+ 1	- 5
0	+ 0	+117	+ 4	-11
-100	-189	-140	- 2	+ 0
-100	-179	- 78	+11	- 2
-100	-197	- 5	- 6	+ 7
-100	-201	+ 59	- 7	+ 8
-100	-198	+115	- 3	+ 0
Mean of absolute values	128.9	79.1	4.5	5.0

V. EVALUATION OF SERIAL NO. LEFT STAGE

A. Measuring Procedure

The measuring procedure was identical to that used at the right stage of this instrument.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The procedure was the same as described previously. The results are presented graphically in Figure 5. The mean magnitude of the errors in the x and y coordinates for the 15 points were found to be:

$$m_x = 0.0124 \text{ mm.} = 12.4 \text{ microns}$$

$$m_y = 0.0085 \text{ mm.} = 8.5 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = +0.0050\% \quad (5.0 \text{ microns per } 100 \text{ mm.})$$

$$dM_y = +0.0084\% \quad (8.4 \text{ microns per } 100 \text{ mm.})$$

and the non-orthogonality of the axes to be:

$$d\beta = +0.000173 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of Axes

Substituting the specific values for the scale errors and non-orthogonality given above in the previously cited adjustment equations results in the following:

$$x_a = (+0.999950)x_m - (0.000173)y_m$$

$$y_a = (+0.999916)y_m$$

The mean magnitude of the errors in the x and y coordinates after adjustment are as follows:

$$m_{x_a} = 0.0063 \text{ mm.} = 6.3 \text{ microns}$$

$$m_{y_a} = 0.0057 \text{ mm.} = 5.7 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the blue lines) for each grid position are given in Table 4, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 50% in the x coordinates and 33% in the y coordinates can be obtained by the utilization of the adjustment equations.

Table 4 - Errors in Grid Coordinates

Instrument Serial Left Stage

STAT

Grid Position (mm)	Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
y_g	e_x	e_y	e_{x_a}	e_{y_a}
+100	+11	+ 0	+ 8	+ 0
+100	+ 5	+ 2	- 3	- 2
+100	+ 7	- 1	- 6	- 9
+100	+16	+ 5	- 2	- 8
+100	+26	+25	+ 3	+ 8
0	- 1	+ 2	+ 9	+10
0	- 9	+ 1	- 4	+ 5
0	- 5	- 3	- 5	- 3
0	+ 1	+ 3	- 4	- 2
0	+18	+ 20	+ 8	+11
-100	-16	-14	+ 7	+ 3
-100	-22	-14	- 4	- 1
-100	-25	-18	-12	- 9
-100	-14	-13	- 6	- 9
-100	+10	+ 6	+13	+ 6
Mean of absolute values:	12.4	8.5	6.3	5.7

REPORT ON EVALUATION OF TWO MENSURATION TABLES AND PRELIMINARY ERROR ANALYSIS

Why "preliminary" - cover letter calls this "the final report" of the contract

STAT

January 1969

[redacted]

I. INTRODUCTION

Evaluations of both stages of two [redacted] mensuration STAT
this "instrument" is the light table itself
light tables were performed through instrument measurements of a calibrated grid. The two mensuration tables are identified as Model No. 552A101,
IEG IAS
STAT Serial Nos. [redacted] In making the measurements, it became apparent the mechanical operating condition of these tables was unsatisfactory, as evidenced by the fact that the same coordinate readings could not be obtained for a given point after the reading head had been moved away from the point and then returned. Probable causes of the incompatible readings are given later. (Pp. 3-7)

what is to follow? Perhaps what is indicated in last sentence of this paragraph

A preliminary error analysis was conducted for each stage to determine the degree of non-orthogonality between the two axes, the scale error along the x-axis, and the scale error along the y-axis. Values derived
but errors indicated on pgs 2,3,8,10,11 are not [illegible]
for these quantities must be approximate due to the non-reproducability of coordinate readings, as mentioned above. The poor operating characteristics of the tables precluded the investigation of minor error sources such as periodic lead screw error and curvature of the ways. Evaluation of these latter errors must await proper operating characteristics, compensation for scale errors in the x and y directions, and alinement of the coordinate axes of the instrument to an orthogonal position.

A. Grid Plate

228.6 x 228.6 mm — presumably a 230 x 230 mm grid

A 9 x 9-inch precision Grid Plate was obtained from the VEB Carl Zeiss Jena Company. An accompanying calibration report indicated the grid graduation was measured at 33 points evenly distributed over the plate. The
[illegible] — of the [illegible] points?
mean errors of position in both coordinate directions relative to an ideal grid (with a mesh size of 10.0000 mm.) defined according to the least squares

method were determined from these measured values. The mean errors of position obtained were as follows:

$$m_x = \pm 0.0008 \text{ mm.}$$

$$m_y = \pm 0.0008 \text{ mm.}$$

± 31.6 μ-in

Mean Grid Errors of 33 points

The graduation errors ascertained with respect to the 33 grid intersections are listed in the calibration report supplied with the grid. However, for purposes of evaluation, error analysis, and alinement to the accuracies specified for these instruments (i.e., distances measured must be accurate to within ±2.5 microns + 0.005% of the distance measured), the grid may be considered "perfect" or error-free.

B. Operator Pointing Error

Replicated x and y coordinate measurements were made at 33 points to determine how well the operator could reset the pointing mark at the grid intersection. The maximum instrument magnification capability (128 X) was used for these measurements and all subsequent evaluation measurements. The width of the grid lines is 15 microns; the diameter of the point mark is also 15 microns at the magnification used (with the pointing mark dot size set at maximum).

Analysis of the replicated readings indicate the standard deviation of one setting to be:

i.e., reading points only once. Reading points twice resulted in lower error - see Pg. 3

$$s_x = \pm 0.0011 \text{ mm.}$$

$$s_y = \pm 0.0011 \text{ mm.}$$

± 43.3 μ-in

Mean Pointing Error One Setting

A pointing accuracy of this precision would be acceptable, but what was the magnitude of these movements

It should be noted the replicated readings were taken without major movements of the optical reading head and it is hoped the mechanical operating problems did not affect these readings, but this cannot be assured. At any rate, the

Coefficient of expansion of Pyrex $= 18.5 \times 10^{-7}$ in/in/°F

For $\Delta T = 30°$, expansion $= 55.5 \times 10^{-6}$ in/in $= 1.4\ \mu$/in pointing accuracy is at least as good as indicated above. Since two readings were taken at all subsequent measurements, the standard error of the average can be found by dividing the standard deviation of one setting by the square root of two or:

$$s_x = \pm 0.0008 \text{ mm.}$$

± 31.6 μ-in

$$s_y = \pm 0.0008 \text{ mm.}$$

Mean Pointing Error Two Settings

Hence, the errors in pointing are of the same order of magnitude as the errors in the grid. operator pointing error – not machine error ?

C. Mechanical Operating Problems

The following erraticisms in mechanical operating characteristics were noted during the evaluation procedure.

(1.) Drift. The most noticeable and identifiable cause of non-reproducability of coordinate readings was drift -- i.e., it was noted that the pointing mark could be set at a grid intersection, and then would drift away from the intersection with time. The coordinate counters did not move during this drift -- i.e., different readings were obtained when the measuring point was moved back to the grid intersection. The following set of readings indicate the variations in coordinate readings for a given point with time. (Note: the x coordinate remained constant; drift occurring in the y direction only.)

Time	y Coordinate Reading (mm.)	
12:16	72.186	
:17	.189	
:18	.190	net change:
:20	.192	12 microns
:22	.194	
:56	.198	

These data were collected at the right stage of Instrument No. [redacted] However, STAT
comparable drifts were noted at the left stage of No. [redacted] and the right stage STAT

but measurement error in this stage is larger than in other stages - see Pg. 23

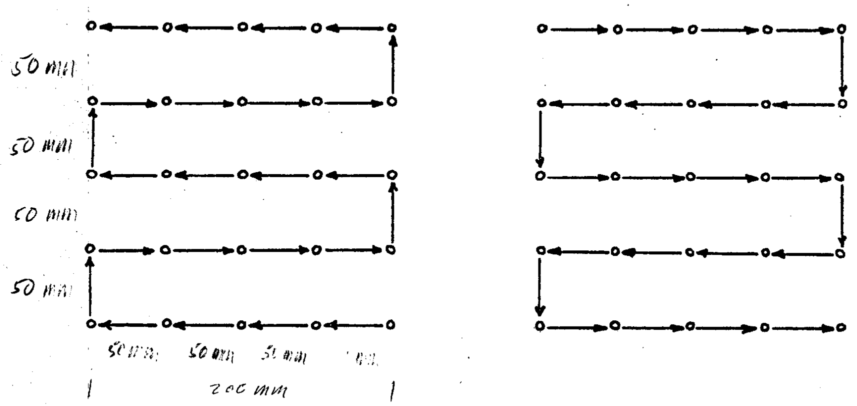
STAT of No. [redacted] In a 15-minute trial, no drift was noted at the left stage of STAT No. [redacted] There was no drift in the x direction at any of the four stages.

Further evidence of the "drift" in y-coordinate readings, and the nature of the drift, can be seen by comparing the readings obtained on two passes over the 25 points measured on the left half of the right stage on STAT Instrument No. [redacted] (There were 5 lines of 5 points each; pass 1 was made in the order shown in Figure 1~~b~~a. The values in Figure 1c are the difference in y readings for the two passes.)

Note that the discrepancy in y-coordinate measurements increased as the time between readings at the points increased -- i.e., the two readings for the point in the upper left corner were taken in succession with little time lapse or movement of the optical head between readings, whereas the series of readings was started with the point in the lower right corner and the pass 2 readings for this point were not taken until the end of the series. Note further that the discrepancies for a given row are fairly consistent and major changes seem to occur between rows. This leads one to suspect the instrument is "binding" in the y motion; the major "binds" occurring when the reading head is moved from one row to the next. A major disruption in the pattern occurs in the fourth row from the top. However, it is possible some of the binding "relaxed" in moving from the fifth point to the fourth point in that row.

It should also be noted that if the instrument was left in the position at which the final reading in pass 2 was obtained, the aforementioned drift tended to bring the instrument back to the original reading -- i.e., the 8 micron discrepancy in the point at the lower right corner in Figure 1 tended to decrease with time. Further, it was noted that if the reading head was

$2\frac{1}{2}$ microns + 0.0[illegible] [illegible]
[illegible] = [illegible]
and repeatability [illegible] in y-direction



(a) Pass 1 (b) Pass 2

1	3	3.	4	2
5	4	4	6	7
6	6	7	6	6
3	3	3	3	7
5	5	7	8	8

(c) y-coordinate discrepancies (microns) (Pass 1 – Pass 2)

Were readings always taken from same direction at each point

Figure 1. Example of Drift in y-Coordinates
(50 mm. grid; Serial [redacted] right stage, left half)

STAT

9

moved rapidly back and forth in the y direction, it was possible to obtain the original reading.

From the above observations, it is hypothesized that the mechanical operation of the instrument is not satisfactory -- i.e., there appears to be a tendency for the reading head to "stick" or "bind" in the y direction. This binding may release gradually, as evidenced by the slow drift of the reading head in the y direction, or in spurts as indicated by the readings in row four in Figure 1.

(2.) "Stuttering." When y motion of the reading head was initiated by the joy stick, a noticeable "stuttering" occurred, clearly visible to the operator as an apparent vibration in the image. Further, when the instrument reading head was in motion in the y direction, a "groaning" noise was clearly audible to the operator or anyone in the immediate vicinity. These observations lend credence to the belief that the y motion of the instrument is not functioning properly.

ILLEGIB

The vibrations and noises were noted at both stages of both instruments.

ILLEGIB

(3.) Variations in focus. Another indication of improper motion in the reading head is the fact that the focus changed as the reading head travelled over the area of the calibration plate -- i.e., the focus could be set f one grid intersection and then, when the reading head was moved to another intersection and another part of the calibration plate, the grid would be slightly out of focus; at still another point, it might be back in focus. This phenomenon indicates the reading head is not moving in a plane parallel to the grid plate. Apparently, the reading head moves in the vertical direction while traversing the grid plate. Again, this could be due to binding in the mechanical operation of the instrument.

say in glass platen as well

It is important that the focusing adjustment not be tampered with during the course of a set of readings. Refocusing can cause a shift of several microns in the position of the measuring mark. This is particularly true for the left stage of Instrument No. [redacted] where a shift of up to 30 microns was noted. The shifts at the other three stages were much smaller. STAT

(4.) Environmental conditions. If the accuracy of the instruments is to be enhanced, and then maintained, it is essential that the temperature in the instrument rooms be kept within a narrow range. Further, it appears that more attention to cleanliness and maintenance will be required. The instruments are quite "dirty" and one suspects they have not been lubricated since their delivery. For the accuracies desired it is probably not essential that perfectly vibration-free floor space be provided for the instruments. However, certain care must be exercised because of the "soft" foundation provided for the instruments by the foot pads. It was noted that a shift in the measuring mark of approximately 8 microns occurred when someone leaned on a corner of the instrument.

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II. EVALUATION OF SERIAL NO. [redacted] RIGHT STAGE

STAT

A. Measuring Procedure

It was not possible to purchase a 9 x 18-inch grid of sufficient quality for the evaluation. A 9 x 9-inch grid plate was purchased, having a rectangular grid mesh of 10 millimeters, and a calibrated accuracy of ± 0.8 microns in both the x and y directions. Not all of the available grid intersections were used in the evaluation procedure -- the spacing between rows and between columns being 50 millimeters for the evaluation. Since the grid plate was roughly half the size of the stage of the instrument, it was necessary to measure the grid plate in two positions. The readings taken with the grid on the right side of the stage were then tied to the readings taken on the left side through the use of a standard rotation-translation transformation based on the grid points along the common edge which overlapped at the center of the stage. In all, then, the total area in which grid measurements were taken was 200 mm. by 400 mm., with a point spacing of 50 mm. (approximately 2 inches); resulting in a 5 x 9 grid (8 x 16-inch), for a total of 45 points.

228.6 x 228.6 mm (230 x 230 mm)

Correlation of two 9x9 grids when measuring 9x18 area

B. Evaluation of the Mensuration Accuracy in the Present Condition

The instrument readings were transformed to the "perfect" grid through the use of a least-squares rotation-translation transformation which maintained the geometric integrity of the instrument readings. This permits one to assess the mensuration accuracy of the instrument in its present state -- i.e., without any corrections or adjustments to the basic readings. (The instrument readings have merely been rotated and translated to give the best fit to the grid; their relative positions have not been changed.) Figure 2

"Instrument Coordinate Readings" on Figure 2

deviations of the best fit grid from the standard   See p. 28

indicates the errors obtained at the instrument in its present state. The black lines represent the perfect grid, and the ~~blue~~ green lines represent the grid as it was measured by the instrument. Note that the errors have been plotted at a greatly exaggerated scale as compared to the scale of the grid. Analysis of the data for Figure 2 indicates the mean magnitudes of the errors in the x and y coordinates for the 45 points to be:

$$m_x = 0.0100 \text{ mm.} = 10.0 \text{ microns}$$

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$$dM_x = +0.0075\% \text{ (7.5 microns per 100 mm.)}$$

$$dM_y = +0.0240\% \text{ (24.0 microns per 100 mm.)}$$

and the non-orthogonality of the axes to be:

$$d\beta = 0.000094 \text{ radians}$$

C. <u>Accuracy After Removal of x and y Scale Errors and Non-orthogonality of Axes</u>

It is possible to remove the effects of x and y scale errors and non-orthogonality of the axes by transformation of the instrument readings through the use of the following transformation equations:

$$x_a = x_m \cdot (1 - dM_x) \; - y_m (d\beta)$$

$$y_a = y_m \cdot (1 - dM_y)$$

where (x_a, y_a) are the coordinates after adjustment and (x_m, y_m) are the measured coordinates. Substituting the values for scale errors and non-orthogonality given in (2) above, the equations become:

$$x_a = (+0.999925)x_m - (0.000094)y_m$$

Corrections to Data as Measured

$$y_a = (+0.999760)y_m$$

(The values for the scale errors and non-orthogonality were determined through the use of a least squares adjustment of the instrument readings from the 45 points.)

The red lines in Figure 2 indicate the values obtained for the grid after adjustment for the scale errors and non-orthogonality of axes. Note the "fit" is considerably improved. The mean magnitudes of the errors in the x and y coordinates after adjustment are as follows:

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$$m_{x_a} = 0.0040 \text{ mm.} = 4.0 \text{ microns}$$

$$m_{y_a} = 0.0031 \text{ mm.} = 3.1 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the ~~blue~~ green lines) for each grid position are given in Table 1, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-othogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 60% in the x coordinates and 79% in the y coordinates can be obtained by the utilization of the adjustment equations.

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To summarize, errors as represented by the blue lines can be expected if the "raw" readings as obtained from the instrument in its p state are utilized; the errors can be reduced to those indicated by the r lines through transformation of the instrument readings utilizing the eq tions given above. However, it must be remembered the effects of dri stuttering have probably been averaged out through the use of the avera replicated readings at the points and the adjustment procedure. Large errors could be encountered if single readings are taken at points distr

Table 1 - Errors in Grid Coordinates

Instrument Serial No. [redacted] Right Stage

STAT

True Grid Position (mm.)		Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
x_g	y_g	e_x	e_y	e_{x_a}	e_{y_a}
-200	+100	-11	+18	- 3	-2
-150	+100	-11	+16	- 7	-4
-100	+100	- 5	+21	- 5	-1
- 50	+100	- 1	+21	- 4	-2
0	+100	+ 4	+29	- 3	+5
+ 50	+100	+14	+28	+ 3	+3
+100	+100	+21	+29	+ 6	+3
+150	+100	+15	+28	- 3	+1
+200	+100	+21	+23	- 1	-5
-200	+ 50	- 6	+ 4	+ 5	-4
-150	+ 50	- 8	+ 3	- 1	-5
-100	+ 50	+ 2	+ 7	+ 6	-3
- 50	+ 50	+ 3	+ 9	+ 3	-2
0	+ 50	+ 8	+15	+ 4	+3
+ 50	+ 50	+16	+14	+ 8	+1
+100	+ 50	+22	+15	+11	+1
+150	+ 50	+16	+14	+ 1	-1
+200	+ 50	+20	+ 7	+ 1	-9
-200	0	-17	+ 0	- 2	+4
-150	0	-19	+ 1	- 8	+5
-100	0	- 7	+ 1	+ 0	+3
- 50	0	- 7	+ 3	- 3	+4
0	0	- 5	+ 7	- 5	+7
+ 50	0	+ 3	+ 4	- 1	+3
+100	0	+12	+ 7	+ 4	+5
+150	0	+ 4	+ 7	- 8	+4
+200	0	+ 9	+ 1	- 6	-3
-200	- 50	-17	-18	+ 2	-2
-150	- 50	-17	-20	- 2	-4
-100	- 50	- 5	-15	+ 6	-1
- 50	- 50	- 7	-12	+ 1	+1
0	- 50	- 4	- 6	+ 0	+6
+ 50	- 50	+ 5	-10	+ 5	+1
+100	- 50	+13	- 7	+ 9	+3
+150	- 50	+ 5	- 7	- 2	+2
+200	- 50	+ 6	-13	- 5	-5
-200	-100	-22	-30	+ 0	-2
-150	-100	-21	-30	- 3	-2
-100	-100	-10	-29	+ 5	-3
- 50	-100	-14	-27	- 3	-2
0	-100	- 8	-21	- 1	+3
+ 50	-100	+ 1	-22	+ 4	+1
+100	-100	+ 7	-20	+ 7	+2
+150	-100	- 2	-22	- 6	-1
+200	-100	+ 0	-27	- 8	-7
Mean of absolute values:		10.0	14.8	4.0	[illegible]

randomly over the stage. Further, the reproducability of the accuracies reported above cannot be guaranteed as the drift effects are not entirely systematic.

The errors remaining after adjustment (i. e., indicated by the red lines of Figure 2 and Columns (5) and (6) of Table 1) are due to aberrations in the mechanical operation of the instrument, periodic lead screw errors, curvature of the ways, errors in the grid (very small), errors in pointing (very small), etc. Differentiation of these errors is not possible due to the "Masking" effects of the mechanical aberrations (drift, binding, etc.).

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III. EVALUATION OF SERIAL NO. [redacted] LEFT STAGE

STAT

A. Measuring Procedure

Preliminary analysis of the data collected at the right stage of Instrument No. [redacted] indicated that it would not be possible to assess minor error sources in the tables in their present condition. Therefore, it was decided to increase the grid spacing to 100 mm. for data collection at the other three stages to be evaluated. The total area in which grid measurements were taken remained 200 mm. by 400 mm.; but with the spacing of 100 mm. (approximately 4 inches), the total number of grid intersections measured was reduced to 15. Otherwise, the measuring procedure was the same as described for the evaluation of the right stage, including the measurement of the plate in two positions and the subsequent tying together to give one set of data.

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Unfortunately, the electronic counter was not operating properly when the measurements were made with the plate on the right half of this stage. When the malfunctioning was noticed, a slight adjustment to the counter was made, and a second set of measurements appeared to be satisfactory. Later, more detailed office computations indicated the measurements were not satisfactory and could not be used in the evaluation process. When the grid plate was moved to the left half of the stage, the faulty electronic counter was replaced. Hence, evaluation of this stage of the instrument is based on coordinate measurements taken at the left half of the stage only. The resultant grid coordinate measurements (from a total of 9 points) are sufficient to provide a general evaluation of this stage. Somewhat higher error values would be expected if data from the total stage area were available, but the available data can be used to determine the presence and magnitude of scale errors in the x and y directions and non-orthogonality of the axes.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The evaluation procedure is similar to that outlined earlier for the right stage of Instrument No. [redacted] Figure 3 indicates the errors obtained at the instrument in its present state. Again, the black lines represent the perfect grid, and the ~~blue~~ green lines represent the grid as it was measured by the instrument. Analysis of the data for Figure 3 indicates the mean magnitudes of the errors in the x and y coordinates for the 9 points to be:

$$m_x = 0.0093 \text{ mm.} = 9.3 \text{ microns}$$

$$m_y = 0.0116 \text{ mm.} = 11.6 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = -0.0042\% \quad (4.1 \text{ microns per } 100 \text{ mm.})$$

$$dM_y = +0.0090\% \quad (9.0 \text{ microns per } 100 \text{ mm.})$$

and the non-orthogonality of the axes to be:

$$d\beta = 0.000247 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of Axes

When the values for the scale errors and non-orthogonality for this stage are substituted in the previously mentioned equations, the resultant adjustment equations are:

$$x_a = (+1.000042)x_m - (0.000247)y_m$$

$$y_a = (+0.999910)y_m$$

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The red lines in Figure 3 indicate the values obtained for the grid after adjustment for the scale errors and non-orthogonality of axes. The mean magnitudes of the errors in the x and y coordinates after adjustment are as follows:

$$m_{x_a} = 0.0017 \text{ mm.} = 1.7 \text{ microns}$$

$$m_{y_a} = 0.0038 \text{ mm.} = 3.8 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the ~~blue~~ green lines) for each grid position are given in Table 2, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). In this case, improvements of 82% in the x coordinates and 68% in the y coordinates can be obtained by the utilization of the adjustment equations. The same qualifications as to the validity of these conclusions mentioned in the discussion of the evaluation of the right stage apply here also.

Table 2 - Errors in Grid Coordinates

Instrument Serial No. [redacted] Left Stage

STAT

True Grid Position (mm.)		Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
x_g	y_g	e_x	e_y	e_{x_a}	e_{y_a}
-200	+100	+14	- 1	- 2	+ 3
-100	+100	+11	+ 7	- 1	- 2
0	+100	+ 9	+26	+ 1	+ 5
-200	0	+ 6	-13	+ 1	- 1
-100	0	+ 2	- 8	+ 2	- 8
0	0	- 2	+11	+ 2	- 1
-200	-100	- 6	-16	+ 2	+ 5
-100	-100	-16	-14	- 3	- 5
0	-100	-18	+ 8	- 1	+ 4
Mean of absolute values:		9.3	11.6	1.7	3.8

IV. EVALUATION OF SERIAL NO. [redacted] RIGHT STAGE

A. Measuring Procedure

The measuring procedure was the same as that described for the left stage of Serial No. [redacted] -- i.e., the grid plate was measured in two positions and then tied together, resulting in a 100 mm. grid spacing and a total of 15 points.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The procedure was the same as described previously. The results are presented graphically in Figure 4. The mean magnitudes of the errors in the x and y coordinates for the 15 points were found to be:

$$m_x = 0.1289 \text{ mm.} = 128.9 \text{ microns}$$

$$m_y = 0.0791 \text{ mm.} = 79.1 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = -0.0025\% \quad (2.5 \text{ microns per } 100 \text{ mm.})$$

$$dM_y = +0.0124\% \quad (12.4 \text{ microns per } 100 \text{ mm.})$$

and the non-orthogonality of the axes to be:

$$d\beta = +0.002555 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of axes.

Substituting the specific values for scale errors and non-orthogonality given above in the previously cited adjustment equations results in the following:

$$x_a = (+1.000025)x_m - (0.002555)y_m$$

$$y_a = (+0.999875)y_m$$

The mean magnitudes of the errors in the x and y coordinates after adjustments are as follows:

$$m_{x_a} = 0.0045 \text{ mm.} = 4.5 \text{ microns}$$

$$m_{y_a} = 0.0050 \text{ mm.} = 5.0 \text{ microns}$$

Note that the original error values for this stage are very high compared to the other three stages. This is due to a very poor relative alignment of the axes -- i.e., the non-~~ortho~~gonality is exceptionally high (0.00256 radians, or approximately $0^\circ 09'$). Note further, however, that the errors after adjustment compare favorably in magnitude with those of the other three stages. Thus, the non-orthogonality can be compensated for adequately through the adjustment equations.

The errors in the raw coordinate readings (indicated by the ~~blue~~ green lines) for each grid position are given in Table 3, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 97% in the x coordinates and 94% in the y coordinates can be obtained by the utilization of the adjustment equations.

Table 3 - Errors in Grid Coordinates

Instrument Serial No. Right Stage

True Grid Position (mm.)		Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
x_g	y_g	e_x	e_y	e_{x_a}	e_{y_a}
-200	+100	+187	-115	- 8	+ 1
-100	+100	+197	- 49	+ 4	+ 2
0	+100	+187	+ 21	- 4	+ 8
+100	+100	+189	+ 83	- 1	+ 7
+200	+100	+191	+135	+ 4	- 5
-200	0	+ 3	-137	- 1	- 9
-100	0	+ 12	- 70	+10	- 6
0	0	- 2	+ 4	- 2	+ 4
+100	0	- 2	+ 59	+ 1	- 5
+200	0	+ 0	+117	+ 4	-11
-200	-100	-189	-140	- 2	+ 0
-100	-100	-179	- 78	+11	- 2
0	-100	-197	- 5	- 6	+ 7
+100	-100	-201	+ 59	- 7	+ 8
+200	-100	-198	+115	- 3	+ 0
Mean of absolute values		128.9	79.1	4.5	5.0

V. EVALUATION OF SERIAL NO. [redacted] LEFT STAGE

STAT

A. Measuring Procedure

The measuring procedure was identical to that used at the right stage of this instrument.

B. Evaluation of the Mensuration Accuracy in the Present Condition

The procedure was the same as described previously. The results are presented graphically in Figure 5. The mean magnitude of the errors in the x and y coordinates for the 15 points were found to be:

$$m_x = 0.0124 \text{ mm.} = 12.4 \text{ microns}$$

$$m_y = 0.0085 \text{ mm.} = 8.5 \text{ microns}$$

Further analysis of the data shows the scale errors in the x and y directions to be:

$$dM_x = +0.0050\% \quad (5.0 \text{ microns per } 100 \text{ mm.})$$

$$dM_y = +0.0084\% \quad (8.4 \text{ microns per } 100 \text{ mm.})$$

and the non-orthogonality of the axes to be:

$$d\beta = +0.000173 \text{ radians}$$

C. Accuracy After Removal of x and y Scale Errors and Non-orthogonality of Axes

Substituting the specific values for the scale errors and non-orthogonality given above in the previously cited adjustment equations results in the following:

$$x_a = (+0.999950)x_m - (0.000173)y_m$$

$$y_a = (+0.999916)y_m$$

The mean magnitude of the errors in the x and y coordinates after adjustment are as follows:

$$m_{x_a} = 0.0063 \text{ mm.} = 6.3 \text{ microns}$$

$$m_{y_a} = 0.0057 \text{ mm.} = 5.7 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the ~~blue~~ green lines) for each grid position are given in Table 4, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes (indicated by the red lines) are given in Columns (5) and (6). Note that improvements of 50% in the x coordinates and 33% in the y coordinates can be obtained by the utilization of the adjustment equations.

Table 4 - Errors in Grid Coordinates

Instrument Serial No. [redacted] Left Stage

True Grid Position (mm.)		Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
x_g	y_g	e_x	e_y	e_{x_a}	e_{y_a}
-200	+100	+11	+ 0	+ 8	+ 0
-100	+100	+ 5	+ 2	- 3	- 2
0	+100	+ 7	- 1	- 6	- 9
+100	+100	+16	+ 5	- 2	- 8
+200	+100	+26	+25	+ 3	+ 8
-200	0	- 1	+ 2	+ 9	+10
-100	0	- 9	+ 1	- 4	+ 5
0	0	- 5	- 3	- 5	- 3
+100	0	+ 1	+ 3	- 4	- 2
+200	0	+18	+ 20	+ 8	+11
-200	-100	-16	-14	+ 7	+ 3
-100	-100	-22	-14	- 4	- 1
0	-100	-25	-18	-12	- 9
+100	-100	-14	-13	- 6	- 9
+200	-100	+10	+ 6	+13	+ 6
Mean of absolute values:		12.4	8.5	6.3	5.7

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VI. COMMENTS AND RECOMMENDATIONS

(1.) The accuracy of the coordinate measurements as obtained from all four stages of the two instruments can be measurably improved through the use of the proper adjustment equations. The set of adjustment equations to be used for the data from each stage are given in the previous section. These equations permit one to compensate for the average x and y scale errors and non-orthogonality of the axes. Secular or periodic lead screw errors are not compensated for by the use of these equations.

The improvement in results which can be expected if these equations are utilized are indicated in the following tabulation.

Table 5 - Summary of Evaluation Results

STAT

Table No.	Stage	Mean Errors in "Raw" Measurements (Microns)		Mean Errors in Adjusted Measurements (Microns)		Improvements (Percent)	
		m_x	m_y	m_{x_a}	m_{y_a}	x	y
	Right	10.0	14.8	4.0	3.1	60	79
	Left	9.3	11.6	1.7	3.8	82	68
	Right	128.9	79.1	4.5	5.0	97	94
	Left	12.4	8.5	6.3	5.7	50	33

It is not possible to make a more detailed error analysis in the presence of the mechanical operation aberations discussed previously (drift, binding, etc.). Also, the derivation of the adjustment equations has been influenced to some degree by the mechanical operation problem. It is felt that most of these effects were compensated for by taking two sets of readings at the grid intersections, using a reverse pattern for the second set.

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Hence, the initial recommendation is that all point measurements be taken twice. A pattern to include all the points should be established; readings should then be taken by traversing this pattern in both directions. The average of the two readings should then be adjusted through utilization of the transformation equations appropriate for that stage.

(2.) Unless reproducability of coordinate readings can be obtained (i.e., the same readings for a given point, independent of the time between readings (and the direction of approach), no further error analysis will be justified; nor can it be expected that the results can be measurably improved beyond those indicated under "adjusted measurements" in Table 5. It is felt that a thorough cleaning and lubrication of the ways and bearings are a necessary initial step. If this simple procedure does not remove the drift and binding, a more thorough analysis of the problem by mechanical and optical engineers will be required.

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These accuracies

(3.) After implementation of recommendations (1) and (2), a major procedural decision must be made. Essentially, several courses of action are possible, requiring widely varying expenditures. These are:

(a) Continue with the procedure outlined in recommendations (1) and (2) above. The results should be at least as good as those indicated in Table 5, and probably will be somewhat improved with removal of the mechanical operation aberations.

(b) Re-evaluation of the stages after removal of the mechanical operation aberations. This would result in more accurate adjustment equations. A minimum of 45 points per stage is suggested if this procedure is to be followed. (With the grid plate available, it is possible to obtain up to 200 point measurements per stage, if desired.)

This course of action would require another data collection effort and preparation of a report similar to this one.

(c) A more extensive evaluation could be made; resulting in better adjustment procedures, but still not requiring mechanical adjustments of the instruments themselves. Visual analysis of the error diagrams attached to this report indicate certain secular lead screw errors and curvature and weave of the ways errors are present. It is believed that it would be possible to define these minor error sources in sufficient detail through measurements of the available grid plate, if measurements were taken at 10 mm. intervals. (A total of 200 points). More deta could be obtained through measurements of special scale as mentioned in the original proposal, but it is theorized that this additional detail is not required to meet the accuracy requirements specified for these instruments.

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Essentially a "correction grid" would be constructed for each stage of each instrument. One could then enter this correction grid with the absolute coordinates of a point and determine the corrections to be applied to the x and y coordinates. This adjustment procedure could be programmed and computerized.

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The principal disadvantage of this course of action is that the adjustment procedures would be tied to specific location on the stages -- i.e., it would be necessary to know the absolute position of the point being measured with respect to a fixed coordinate system on the stage. This could be accomplished if two points off the photograph were measured with each set of photo coordinates taken at the stage. While the procedure is fairly simple, operational complications may arise if several instrument operators and data reduction specialists are employed.

This course of action, then, would require extensive grid measurements, analysis of the data, and preparation of the correction grids. No instrumental adjustments would be required, but the adjustment procedure would have to be employed at all times, for the raw coordinates would be of the same quality as are being obtained presently.

(d) Alignment of the table. This course of action will be, by far, the most expensive. However, the mensuration tables could then be employed in the manner in which they were originally conceived -- i.e., the raw coordinates at any position on the table could be used as data inputs for any further analytical purposes. It should be possible to mechanically remove the non-orthogonality of the axes, and the curvature and weave of the ways.

How does he know

It is believed the lead screws are not of sufficient quality to provide the desired accuracies. Relatively large scale errors and secular lead screw errors are present, as evidenced in the data collected for this initial evaluation. Better determination of these errors can come only through more extensive evaluation procedures, as mentioned above. It is theorized that adequate results can be obtained through calibration and adjustment of the resultant coordinate readings ((c) above), but that the lead screws must be replaced if the raw instrument readings are ever to meet the accuracy specifications.

These were compared to the best real [illegible]

(The writer is not familiar with the mechanical configuration of these instruments. It is reported by others that scale errors and secular lead screw errors may be removed if the instrument is equipped with a correction bar, fitted with a milled slot or riding edge. It is felt that it is unlikely that these particular instruments are so equipped. The screws are adequate to provide readings to one millimeter, the least count readout capability of the instruments in their original state. ? It is not likely that the instruments were constructed with lead screws capable of measuring to 0.001 mm., and then equipped with a least count readout of one millimeter, as there would be a significant cost differential in the quality of lead screws required. At any rate, since it was impossible to obtain readings to any accuracy greater than one millimeter until the new electronic counters were installed, it would have been impossible for the original manufacturer to evaluate the instruments to any greater accuracy.)

Summary

Results can be considerably improved through the utilization of the appropriate adjustment equations. However, the desired accuracy for these instruments (i.e., distances measured must be accurate to within ± 2.5 microns plus 0.005% of the distance measured), will not be met.

In general, the mean errors in positions will be approximately 6 microns; distances, which involve differences in two positions, can be expected to have a mean error of roughly 8 microns. These values should be considered as "order of magnitude" values only -- they are not "statistically correct" due to the masking effects of the mechanical operation aberations and generalization of values over the four stages evaluated.

Drift and binding of the readings heads must be removed or the errors in individual readings could be considerably higher. After removal of the mechanical operational problems, it will be possible to derive better adjustment equations, including statistical estimates of the degree of confidence to be placed in these equations.

A more extensive calibration procedure, utilizing "correction grids", can be derived and will <u>probably</u> reduce the residual errors to within the desired accuracies. However, considerable flexibility in the measuring and data handling procedures will be lost.

If it is necessary to bring the capabilities of the instrument itself into line with the desired accuracies, it is believed that the existing lead screws must be replaced with high precision lead screws with much smaller scale errors and tolerable periodic and secular errors. It is felt that it will then be possible to remove the other error sources in the instruments (non-orthogonality, curvature and weave of the ways) and derive coordinate measurements within the stated tolerances.

ALTERNATIVE COURSES OF ACTION

1. Eliminate/the mechanical operation aberrations (drift, stuttering, etc.). It may be possible to accomplish this in-house (inspection, cleaning, lubrication, by in-house technicians). [redacted] has no special qualifications in this area. If in-house personnel cannot solve problems it is suggested the original manufacturer should be approached. STAT

2. Determine real accuracy requirements. Some uncertainties seemed to exist earlier. If position accuracy of roughly 6-10 microns or more can be tolerated, implement step 3; if higher accuracies are required (1-4 microns), implement step 4.

3. Two approaches are possible: (a) calibration with no instrument alignment and adjustment, and (b) alignment and adjustment of the instruments (retaining existing lead screws).

    a. Adjustment equations similar to the ones presented in this report could be derived. These are universal in that one set of equations (x and y) can be employed for the entire stage and the absolute location of the photo point need not be known. The adjustment equations derived from the initial evaluation (see attached report) could be used, but there is a good chance the results could be improved to near the lower end of the 6-10 micron range if an evaluation were made after removal of the mechanical operation aberrations.

        (i) Principal advantage: no mechanical or optical modifications to the instruments would be required (beyond that in step 1).

        (ii) Primary disadvantage: all coordinate readings must be adjusted through the appropriate stage-specific adjustment equations. The accuracy of the raw coordinate readings would be no better than in the present state.

STAT [redacted] is prepared to perform the evaluations and formulate the adjustment equations.

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b. Alignment of the existing lead screws and removal of the major curvature and weave of the ways errors could produce better results than are presently being obtained. However, the scale errors in the lead screws range up to 0.024%; creating errors of up to 24 microns per 100 mm. of travel. It is felt unlikely that these can be removed by mechanical adjustment, but this problem should be referred to mechanical-optical engineers.

(i) Principal advantage: coordinate readings could be used directly; no adjustments necessary.

(ii) Primary disadvantage: relatively large errors will still be obtained, with considerable variation between stages. On the average, errors will be in the neighborhood of $\pm$ 6 microns + 0.015% of the distance between points. (This contrasts with a stated desired accuracy of $\pm$ 2.5 microns + 0.005% of the distance between points -- i.e., actual errors will be roughly 3 times that desired; individual errors may be considerably larger than that.) If mechanical adjustment of lead screw scale errors is possible, considerably better results could be obtained. After alignment and adjustment, an evaluation similar to the one just performed will be required.

STAT

[redacted] has no special competence in the instrument modification area, and suggests the original equipment manufacturer be contacted for services in this line. [redacted] is willing to do the evaluation, if desired. STAT

4. Again two approaches are possible: (a) calibration with no instrument alignment and adjustment, and (b) replacement of the lead screws and alignment of the ways.

(a) Use of a calibrated grid will <u>probably</u> produce results approximating the accuracy desired -- ($\pm$ 2.5 microns + 0.005 per cent of the distance measured) -- without major component replacement or alignment. Reproducability of coordinate readings is a requisite, however -- i.e., step 1 must be accomplished. With the calibrated grid, corrections in x and y can be applied to each set of photo coordinate readings, dependent on the absolute position of the photo point on the stage.

(i) Principal advantage: accurate results can be obtained with no major equipment modifications required.

(ii) Principal disadvantage: extensive evaluation and calibration procedures will be required. (Rough estimate: approximately 5 times the effort required for the initial evaluation.) Absolute positions of each photo point must be known. This requires reading coordinates of 2 fixed points off the photo everytime a new photo is to be measured, and every time the coordinate re-indexing capability is utilized. The procedure, although fairly simple, must be thoroughly understood by each comparator operator and initial data analyst. This may create operational problems if several operators and analysts are involved.

STAT [redacted] is willing to prepare the calibration grids.

(b) Replacement of the lead screws and alignment of the tables. It is felt that new, precision lead screws will be required if accurate coordinate readings are to be obtained directly (i.e., without adjustment or use of a calibration grid). It is probable that the errors due to curvature and weave of the ways can be removed through alignment or minor mechanical modifications.

(i) Principal advantage: coordinate readings can be used directly as taken from the electronic counters. In other words, the instruments could be used in the manner originally intended -- as standard comparators.

(ii) Principal disadvantage: relatively high costs and engineering complexity involved in replacing screws and making major modifications. After modification, an evaluation similar to the one just performed will be required.

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[redacted] has no special competence in the instrument modification area, and suggests the original equipment manufacturer be contacted for services in this line. [redacted] is willing to do the evaluation, if desired.

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REPORT ON EVALUATION OF TWO MENSURATION TABLES AND PRELIMINARY ERROR ANALYSIS

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REPORT ON EVALUATION OF TWO MENSURATION TABLES
AND PRELIMINARY ERROR ANALYSIS

Evaluations of both stages of two [redacted] mensuration light tables were performed through instrument measurements of a calibrated grid. The two mensuration tables are identified as Model No. 552A101, Serial Nos. [redacted] In making the measurements, it became apparent the mechanical operating condition of these tables was unsatisfactory, as evidenced by the fact that the same coordinate readings could not be obtained for a given point after the reading head had been moved away from the point and then returned. Probable causes of the incompatible readings are given later. STAT STAT

A preliminary error analysis was conducted for each stage to determine the degree of non-orthogonality between the two axes, the scale error along the x-axis, and the scale error along the y-axis. Values derived for these quantities must be approximate due to the non-reproducability of results mentioned above. The poor operating characteristics of the tables precluded the investigation of minor error sources such as periodic lead screw error and curvature of the ways. Evaluation of these latter errors must await proper operating characteristics, compensation for scale errors in the x and y directions, and alinement of the coordinate axes of the instrument to an orthogonal position.

but errors indicated on pgs. 2,3,8,10,11 do not appear very "approximate".

A. Grid Plate

A 9 x 9-inch precision Grid Plate was obtained from the VEB Carl Ziess Jena Company. An accompanying calibration report indicated the grid graduation was measured at 33 points evenly distributed over the plate. The mean errors of position in both coordinate directions relative to an ideal grid (with a mesh size of 10.0000 mm.) defined according to the least squares method were determined from these measured values. The mean errors of position obtained were as follows:

$$m_x = \pm\ 0.0008 \text{ mm.} \qquad \pm 0.8\ \mu \quad \pm 31.6\ \mu\text{-in}$$
$$m_y = \pm\ 0.0008 \text{ mm.}$$

The graduation errors ascertained with respect to the 33 grid intersections are listed in the calibration report. However, for purposes of evaluation, error analysis, and alinement to the accuracies specified for these instruments (i.e., distances measured must be accurate to within ± 2.5 microns + 0.005% of the distance measured), the grid may be considered "perfect" or error-free.

B. Operator Pointing Error

Replicated x and y coordinate measurements were made at 33 points to determine how well the operator could reset the pointing mark at the grid intersection. The maximum instrument magnification capabilities (128 X) was used for these measurements and all subsequent evaluation measurements. The width of the grid lines is 15 microns; the diameter of the point mark is also 15 microns at the magnification used (with the pointing mark dot size set at maximum).

Analysis of the replicated readings indicate the standard deviation of 1 setting to be:

$$s_x = \pm\ 0.0011 \text{ mm.} \qquad \pm 1.1\ \mu \quad \pm 43.3\ \mu\text{-in}$$
$$s_y = \pm\ 0.0011 \text{ mm.}$$

It should be noted the replicated readings were taken without major movements of the optical reading head and it is hoped the mechanical operating problems did not affect these readings, but this cannot be assured. At any rate, the pointing accuracy is at least as good as indicated above. Since two readings were taken at all subsequent measurements, the standard error of the average can be found by dividing the standard deviation of one setting by the square root of 2, or:

$$s_x = \pm\ 0.0008 \text{ mm.} \qquad \pm\ 0.8\ \mu$$
$$s_y = \pm\ 0.0008 \text{ mm.} \qquad \pm\ 31.6\ \mu\text{-in}$$

Hence, the errors in pointing are of the same order of magnitude as the errors in the grid.

C. Mechanical Operating Problems

The following erraticisms in mechanical operating characteristics were noted during the evaluation procedure.

1. Drift. The most noticeable and identifiable cause of non-reproducability of coordinate readings was drift -- i.e., it was noted that the pointing mark could be set at a grid intersection, and then would drift away from the intersection with time. The coordinate counters did not move during this drift -- i.e., different readings were obtained when the measuring point was moved back to the grid intersection. The following set of readings indicate the variations in coordinate readings for a given point with time. (Note: the x-coordinate remained constant; drift occurring in the y-direction only.)

Time	y-Coordinate Reading (mm.)	
12:16	72.186	
:17	.189	
:18	.190	net change:
:20	.192	12 microns
:22	.194	
:56	.198	

These data were collected at the right stage of Instrument No. [redacted] However, comparable drifts were noted at the left stage of No. [redacted] and the right stage of No. [redacted] In a 15-minute trial, no drift was noted at the left stage of No. [redacted] There was no drift in the x-direction at any of the four stages.

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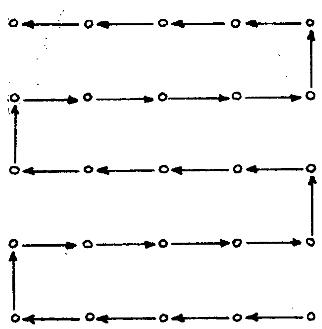
Further evidence of the "drift" in y-coordinate readings, and the nature of the drift, can be seen by comparing the readings obtained on two passes over the 25 points measured on the left half of the right stage on

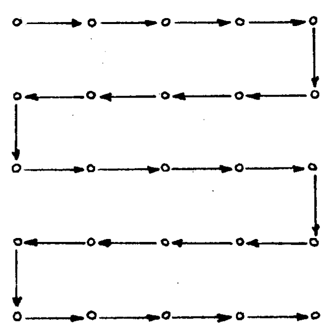
Instrument No. [redacted] (There were 5 lines of 5 points each; pass 1 was made in the order shown in Figure 1a, pass two immediately thereafter in the order shown in Figure 1b. The values in Figure 1c are the difference in y-readings for the two passes.)

Note that the discrepancy in y-coordinate measurements increased as the time between readings at the points increased -- i.e., the two readings for the point in the upper left corner were taken in succession with little time lapse or movement of the optical head between readings, whereas the series of readings was started with the point in the lower right corner and the pass two readings for this point was not taken until the end of the series. Note further that the discrepancies for a given row are fairly consistent and major changes seem to occur between rows. This leads one to suspect the instrument is "binding" in the y motion; the major "binds" occurring when the reading head is moved from one row to the next. A major disruption in the pattern occurs in the fourth row from the top. However, it is possible some of the binding "relaxed" in moving from the fifth point to the fourth point in that row.

It should also be noted that if the instrument was left in the position at which the final reading in pass 2 was obtained, the aforementioned drift tended to bring the instrument back to the original reading -- i.e., the 8 micron discrepancy in the point at the lower right corner in Figure 1 tended to decrease with time. Further, it was noted that if the reading head was moved rapidly back and forth in the y-direction, it was possible to obtain the original reading.



(a) Pass 1



(b) Pass 2

Were reading always taken from same direction at each point

1	3	3	4	2
5	4	4	6	7
6	6	7	6	6
3	3	3	3	7
5	5	7	8	8

(c) y-coordinate discrepancies (microns) (Pass 1 – Pass 2)

Figure 1. Example of Drift in y-Coordinates (50 mm. grid; Serial No. [redacted], right stage, left half)

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From the above observations, it is hypothesized that the mechanical operation of the instrument is not satisfactory -- i.e., there appears to be a tendency for the reading head to "stick" or "bind" in the y-direction. This binding may release gradually, as evidenced by the slow drift of the reading head in the y direction, or in spurts as indicated by the readings in row four in Figure 1.

2. "Stuttering." When y motion of the reading head was initiated by the joy stick, a noticeable "stuttering" occurred, clearly visible to the operator as an apparent vibration in the image. Further, when the instrument reading head was in motion in the y direction, a "groaning" noise was clearly audible to the operator or anyone in the immediate vicinity. These observations lend credence to the belief that the y motion of the instrument is not functioning properly.

The vibrations and noises were noted at both stages of both instruments.

3. Variations in focus. Another indication of improper motion in the reading head is the fact that the focus changed as the reading head travelled over the area of the calibration plate -- i.e., the focus could be set for one grid intersection and then, when the reading head was moved to another intersection and another part of the calibration plate, the grid would be slightly out of focus; at still another point, it might be back in focus. This phenomenon indicates the reading head is not moving in a plane parallel to the grid plate. Apparently, the reading head moves in the vertical direction while traversing the grid plate. Again, this could be due to binding in the mechanical operation of the instrument.

It is important that the focusing adjustment not be tampered with during the course of a set of readings. Refocusing can cause a shift of several microns in the position of the measuring mark. This is particularly true for the left stage of instrument No. [redacted] where a shift of up to 30 microns STAT was noted. The shifts at the other three stages were much smaller.

4. Environmental conditions. If the accuracy of the instruments is to be enhanced, and then maintained, it is essential that the temperature in the instrument rooms be kept within a narrow range. Further, it appears that more attention to cleanliness and maintenance will be required. The instruments are quite "dirty" and one suspects they have not been lubricated since their delivery. For the accuracies desired it is probably not essential that perfectly vibration-free floor space be provided for the instruments. However, certain care must be exercised because of the "soft" foundation provided for the instruments by the foot pads. It was noted that a shift in the measuring mark of approximately 8 microns occurred when someone leaned on a corner of the instrument.

STAT D. Evaluation of Serial No. [redacted] Right Stage

1. Measuring procedure. It was not possible to purchase a 9 x 18-in. grid of sufficient quality for the evaluation. A 9 x 9-in. grid plate was purchased, having a rectangular grid mesh of 10 millimeters, and a calibrated accuracy of ±0.8 microns in both the x and y directions. Not all of the available grid intersections were used in the evaluation procedure -- the spacing between rows and between columns being 50 millimeters for the evaluation. Since the grid plate was roughly half the size of the stage of the instrument, it was necessary to measure the grid plate in two positions. The readings taken with the grid on the right side of the stage were then tied to the readings taken on the left side through the use of a standard rotation-translation transformation based on the grid points along the common edge which overlapped at the center of the stage. In all, then, the total area in which grid measurements were taken was 200 mm. by 400 mm., with a point

spacing of 50 mm. (approximately 2 inches); resulting in a 5 x 9 grid (8 x 16-in.), for a total of 45 points.

2. Evaluation of the mensuration accuracy in the present condition. The instrument readings were transformed to the "perfect" grid through the use of a least-squares rotation-translation transformation which maintained the geometric integrity of the instrument readings. This permits one to assess the mensuration accuracy of the instrument in its present state -- i.e., without any corrections or adjustments to the basic readings. (The instrument readings have merely been rotated and translated to give the best fit to the grid; their relative positions have not been changed.) Figure 2 indicates the errors obtained at the instrument in its present state. The black lines represent the perfect grid, and the red lines represent the grid as it was measured by the instrument. Note that the errors have been plotted at a greatly exaggerated scale as compared to the scale of the grid. Analysis of the data for Figure 2 indicates the mean magnitudes of the errors in the x and y coordinates for the 45 points to be:

m_x = 0.0095 mm. = 9.5 microns   375 μ-in
m_y = 0.0157 mm. =15.7 microns   619 μ-in

Further analysis of the data shows the scale errors in the x and y directions to be:

dM_x = +0.007486% (7.5 microns per 100 mm.)
dM_y = +0.023959% (24.0 microns per 100 mm.)

and the non-orthogonality of the axes to be:

$d\beta$ = 0.000096478 radians   19.9 arc-sec

3. Accuracy after removal of x and y scale errors and non-orthogonality of axes. It is possible to remove the effects of x and y scale errors and non-orthogonality of the axes by transformation of the instrument readings through the use of the following transformation equations:

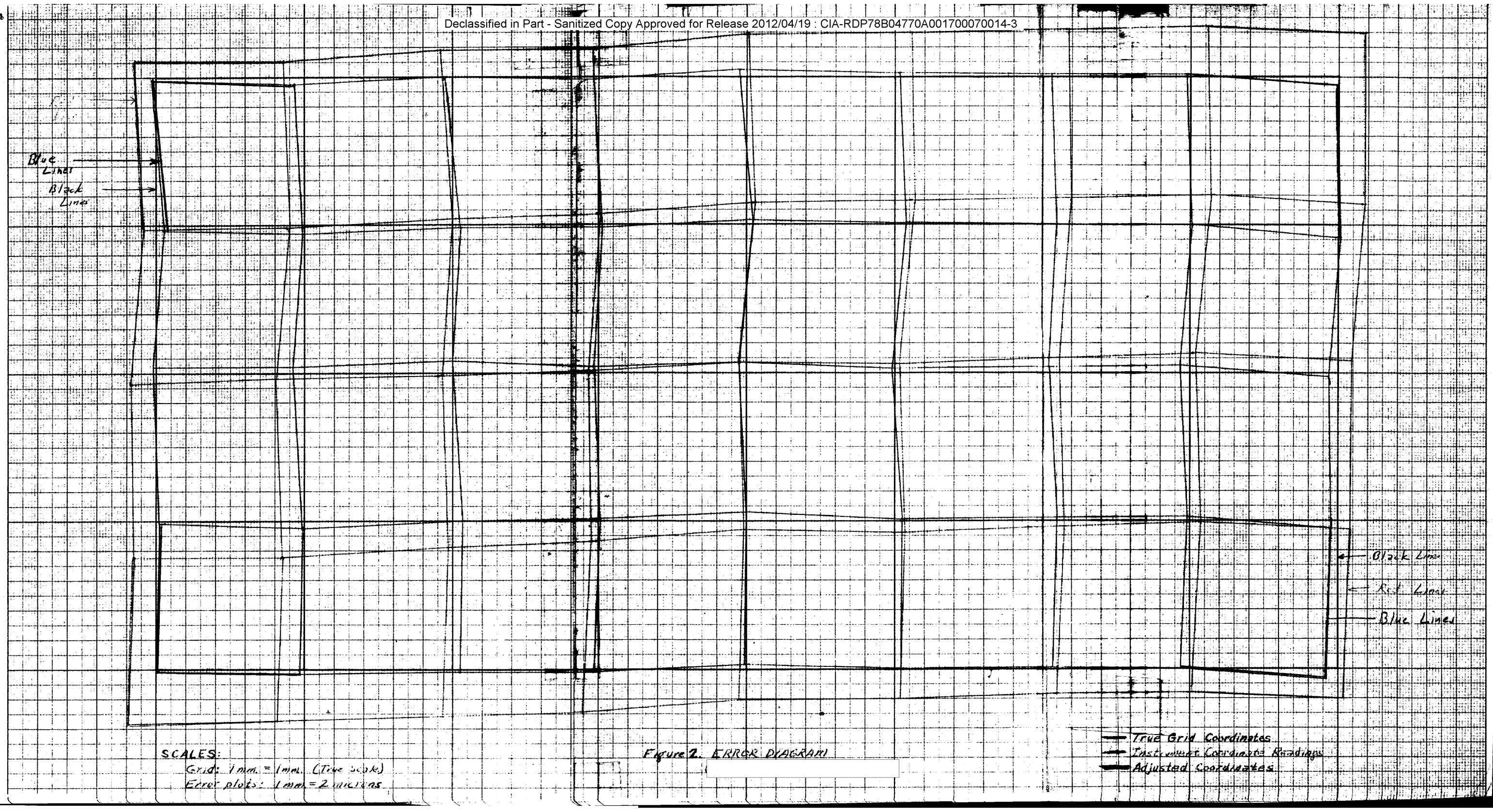

Figure 2. ERROR DIAGRAM

$$x_a = x_m \cdot (1-dM_x) - y_m (d\beta)$$

$$y_a = y_m \cdot (1-dM_y)$$

where (x_a, y_a) are the coordinates after adjustment and (x_m, y_m) are the measured coordinates. Substituting the values for scale errors and non-orthogonality given in (2) above, the equations become:

$$x_a = (+0.99992514)x_m - (0.000096478)y_m$$

$$y_a = (+0.99976041)y_m$$

(The values for the scale errors and non-orthogonality were determined through the use of a least squares adjustment of the instrument readings from the 45 points.)

The blue lines in Figure 2 indicate the values obtained for the grid after adjustment for the scale errors and non-orthogonality of axes. Note the "fit" is considerably improved. The mean magnitudes of the errors in the x and y coordinates after adjustment are as follows:

$$m_x = 0.0041 \text{ mm.} = 4.1 \text{ microns}$$

$$m_y = 0.0030 \text{ mm.} = 3.0 \text{ microns}$$

The errors in the raw coordinate readings (indicated by the red lines) for each grid position are given in Table 1, Columns (3) and (4); the errors after adjustment of the coordinates for x and y scale errors and non-orthogonality of the axes are given in Columns (5) and (6). Note that improvements of 57% in the x coordinates and 81% in the y coordinates can be obtained by the utilization of the adjustment equations.

To summarize, errors as represented by the red lines can be expected if the "raw" readings as obtained from the instrument in its present state are utilized; the errors can be reduced to those indicated by the blue lines through transformation of the instrument readings utilizing the equations given above. However, it must be remembered the effects of drift and stuttering have probably been

Table 1. Errors in Grid Coordinates:

Instrument Serial [redacted] Right Stage

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True Grid Position (mm.)		Errors in "Raw" Measurements (Microns)		Errors after Adjustment (Microns)	
x_g	y_g	e_x	e_y	e_{x_a}	e_{y_a}
-200	+100	-14	+11	- 3	- 2
-150	+100	-14	+11	- 7	- 5
-100	+100	- 8	+18	- 5	0
- 50	+100	- 4	+19	- 4	- 2
0	+100	+ 1	+29	- 5	+ 5
+ 50	+100	+11	+30	+ 3	+ 3
+100	+100	+18	+32	+ 6	+ 2
+150	+100	+12	+34	- 3	+ 2
+200	+100	+18	+30	- 1	- 5
-200	+ 50	- 8	- 3	+ 5	- 4
-150	+ 50	-10	- 2	- 1	- 6
-100	+ 50	0	+ 4	+ 5	- 2
- 50	+ 50	+ 1	+ 7	+ 3	- 2
0	+ 50	+ 6	+15	+ 4	+ 3
+ 50	+ 50	+14	+16	+ 8	+ 1
+100	+ 50	+20	+18	+10	0
+150	+ 50	+14	+20	+ 1	0
+200	+ 50	+18	+14	+ 1	- 9
-200	0	-17	- 7	- 2	+ 4
-150	0	-19	- 4	- 8	+ 4
-100	0	- 7	- 2	0	+ 4
- 50	0	- 7	+ 1	- 3	+ 4
0	0	- 5	+ 7	- 5	+ 7
+ 50	0	+ 3	+ 6	- 1	+ 3
+100	0	+12	+10	+ 5	+ 4
+150	0	+ 4	+13	- 7	+ 5
+200	0	+ 9	+ 8	- 6	- 3
-200	- 50	-15	-25	+ 2	- 2
-150	- 50	-15	-25	- 2	- 5
-100	- 50	- 3	-18	+ 7	0
- 50	- 50	- 5	-14	+ 1	+ 1
0	- 50	- 2	- 6	0	+ 6
+ 50	- 50	+ 7	- 8	+ 5	+ 1
+100	- 50	+15	- 4	+10	+ 2
+150	- 50	+ 7	- 1	- 2	+ 3
+200	- 50	+ 8	- 6	- 5	- 5
-200	-100	-19	-37	0	- 2
-150	-100	-18	-35	- 3	- 3
-100	-100	- 7	-32	+ 5	- 2
- 50	-100	-11	-29	- 3	- 2
0	-100	- 5	-21	- 1	+ 3
+ 50	-100	+ 4	-20	+ 4	+ 1
+100	-100	+10	-17	+ 7	+ 1
+150	-100	+ 1	-16	- 6	0
+200	-100	+ 3	-20	- 8	- 7
Mean of absolute values:		9.5	15.7	4.1	3.0

averaged out through the use of the average of replicated readings at the points and the adjustment procedure. Larger errors could be encountered if single readings are taken at points distributed randomly over the stage. Further, the reproducability of the accuracies reported above cannot be guaranteed as the drift effects are not entirely systematic.

The errors remaining after adjustment (i.e., indicated by the blue lines of Figure 2 and Columns (5) and (6) of Table 1) are due to aberrations in the mechanical operation of the instrument, periodic lead screw errors, curvature of the ways, errors in the grid (very small), errors in pointing (very small), etc. Differentiation of these errors is not possible due to the "masking" effects of the mechanical aberrations (drift, binding, etc.).

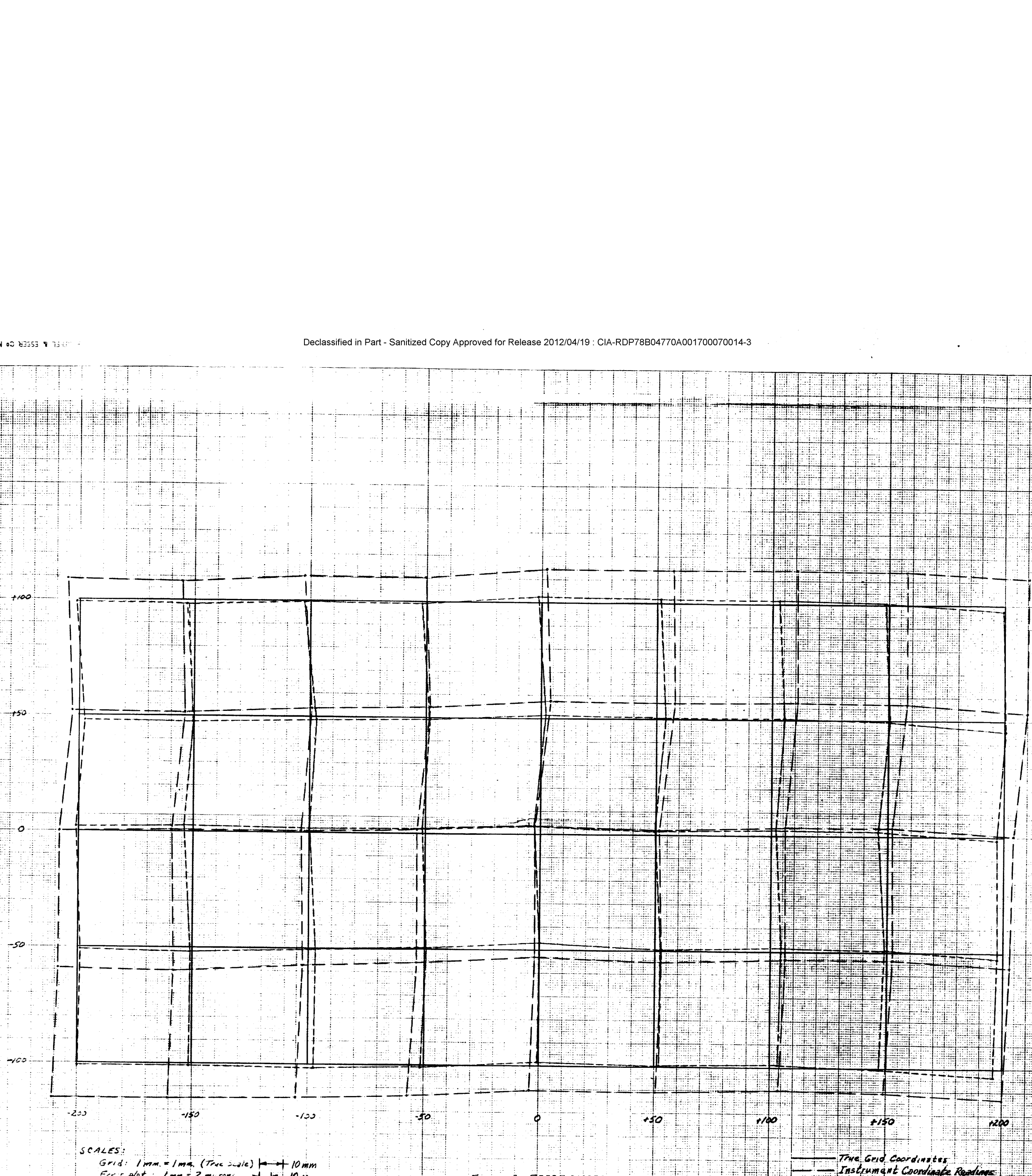

Figure 2. ERROR DIAGRAM

Right Stage

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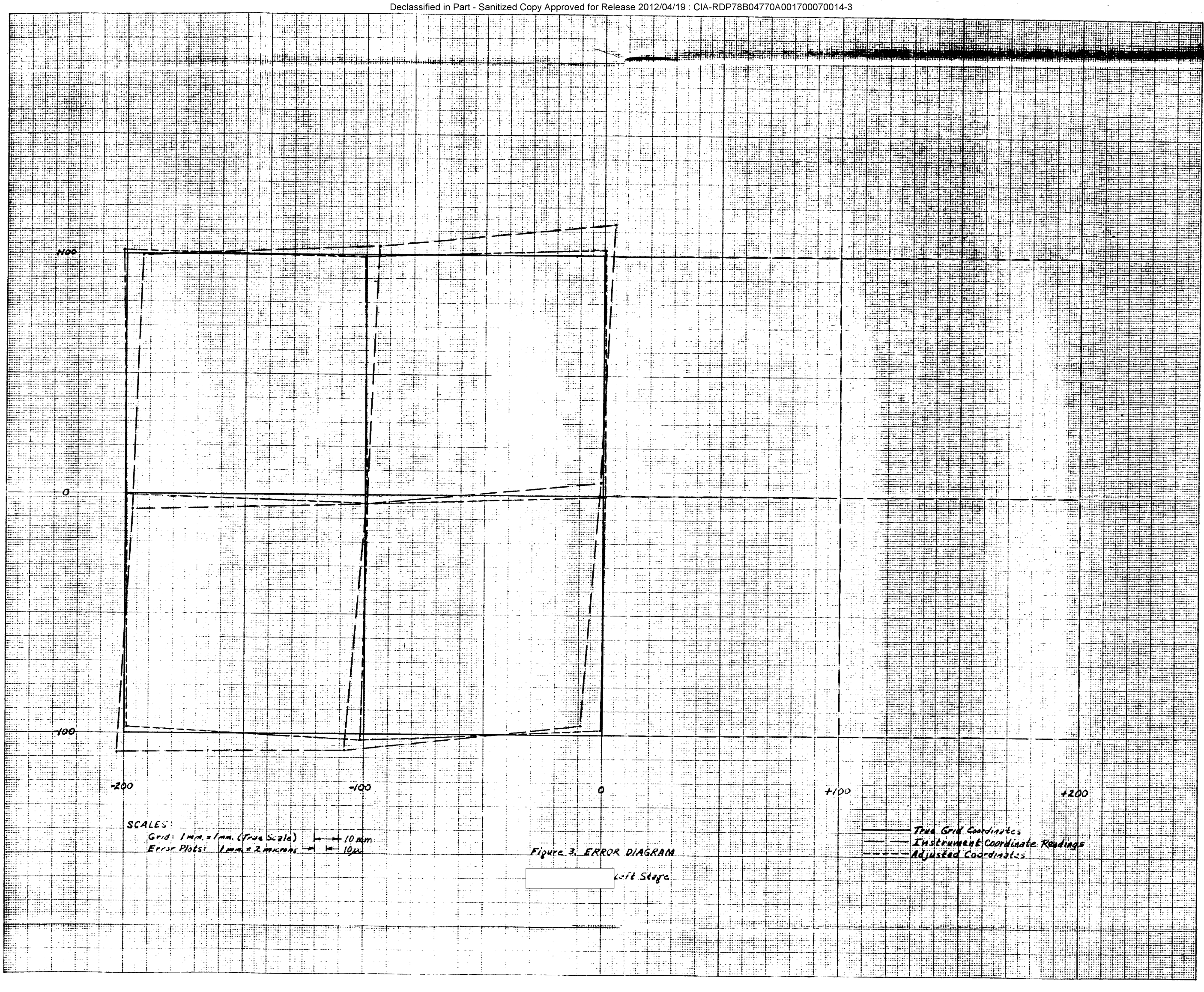

Figure 3. ERROR DIAGRAM

STAT [redacted] Left Stage

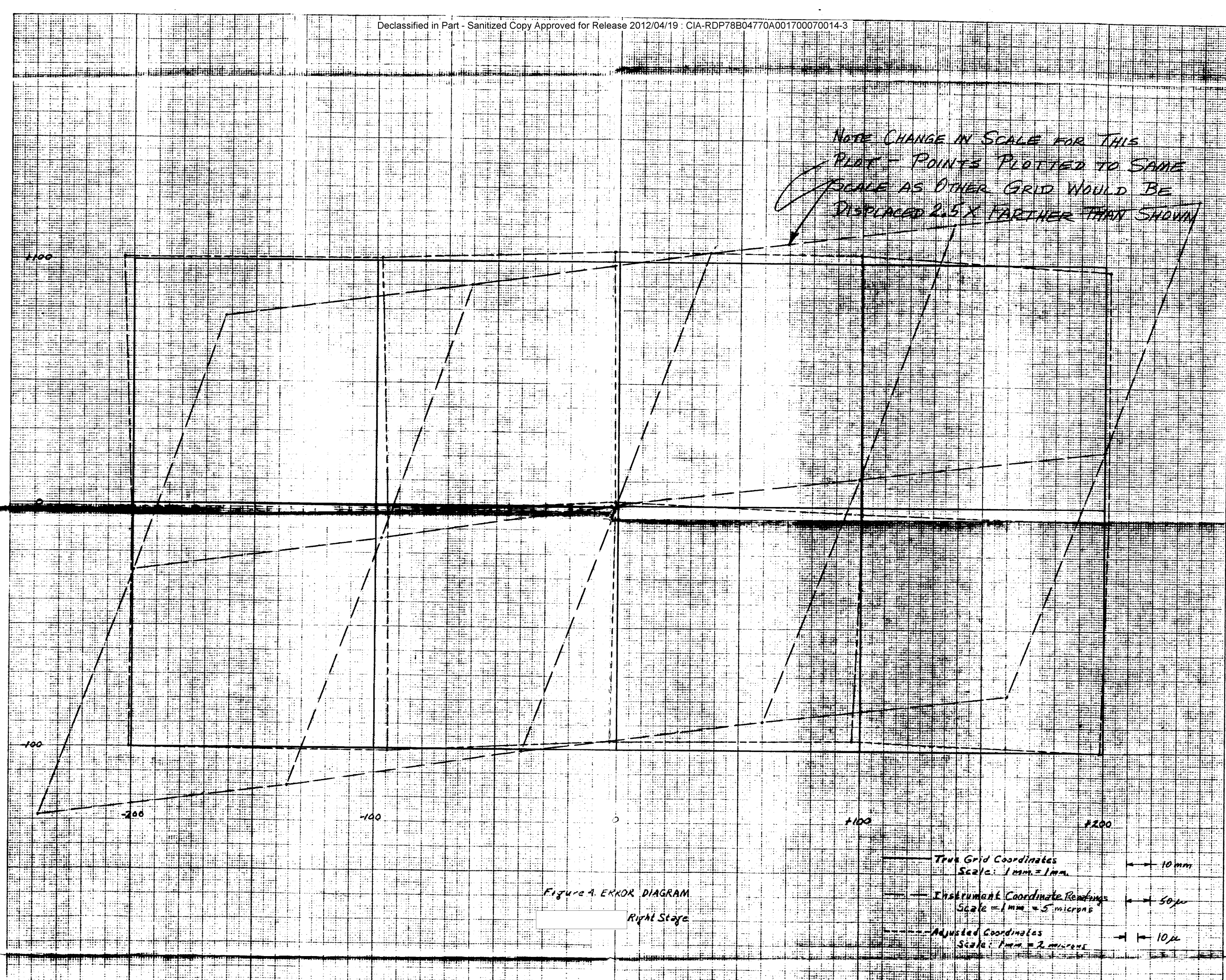

Figure 4. ERROR DIAGRAM
Right Stage

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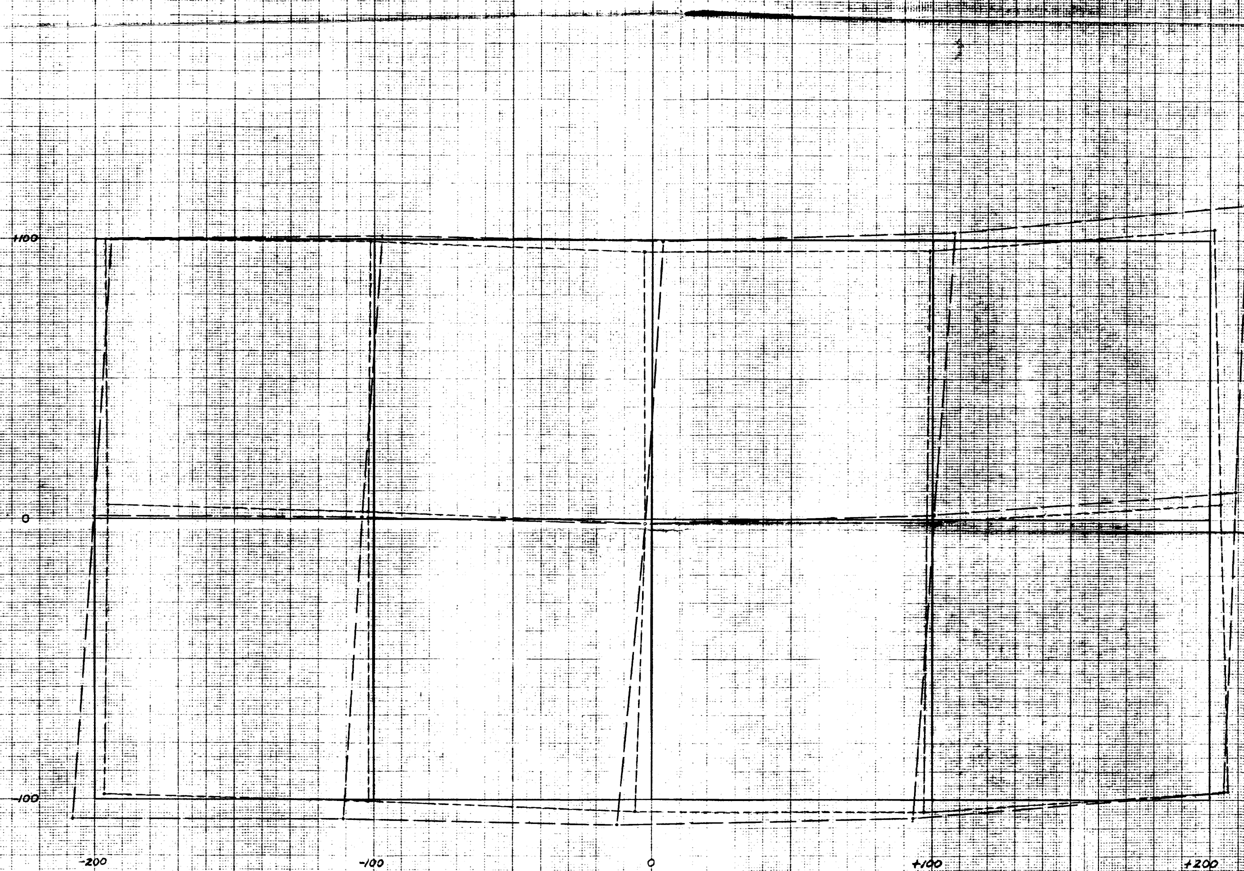

SCALES:
Grid: 1mm. = 1mm (True Scale) 10mm
Error Plots: 1mm = 2 microns 10μ

True Grid Coordinates
Instrument Coordinate Readings
Adjusted Coordinates

Figure 5. ERROR DIAGRAM

it Stage